Fermi National Accelerator Laboratory

FERMILAB-Conf-86/18-A
January 1986

A COSMOLOGIST'S TOUR THROUGH THE NEW PARTICLE ZOO (CANDY SHOP?)

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To be published in Dark Matter in the Universe, eds. J. Knapp and J. Kormendy (Reidel, 1986), proceedings of IAU Symposium 117, held at Princeton, June 24-28, 1985.

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ABSTRACT. Recent developments in elementary particle physics have led to a renaissance in cosmology, in general, and in the study of structure formation, in particular. Already, the study of the very early ($t \lesssim 10^{-2}$ sec) history of the Universe has provided valuable hints as to the 'initial data' for the structure formation problem -- the nature and origin of the primeval density inhomogeneities, the quantity and composition of matter in the Universe today, and numerous candidates for the constituents of the ubiquitious dark matter. I review the multitude of WIMP candidates for the dark matter provided by modern particle physics theories, putting them into context by briefly discussing the theories which predict them. I also review their various birth sites and birth processes in the early Universe. At present the most promising candidates seem to be a 30 or so eV neutrino, a few GeV photino, or the 'invisible axion' (weighing in at about 10^{-5} eV!), with a planck mass monopole, quark nuggets, and shadow matter as the leading 'dark' horse candidates. I also mention some very exotic possibilities -- unstable WIMPs, cosmic strings, and even the possibility of a relic cosmological term.

1. INTRODUCTION

The hot big bang model (also known as the standard model of cosmology) is almost universally accepted -- and for good reason. The model provides a reliable description of the evolution of the Universe from the epoch of primordial nucleosynthesis ($t \simeq 10^{-2}$sec, $T \simeq 10$ MeV) until the present ($t \simeq 15$ Byr, $T \simeq 3$ K). [For a review of the standard cosmology and primordial nucleosynthesis, see Audouze (1986), Boesgaard and Steigman (1986), and Steigman (1986).] Within the context of the standard cosmology there is a general picture of how the structure in the Universe which is so conspicuous today formed -- small primordial density inhomogeneities ($\delta\rho/\rho \simeq 10^{-4}$-$10^{-5}$) began to grow via the Jeans instability when the Universe became matter-dominated, eventually becoming the highly nonlinear structures we observe today, galaxies, clusters of galaxies, etc. [For a recent review of structure formation see Efstathiou and Silk (1983).]

The structure formation problem can be viewed as an initial data problem. The initial epoch being the onset of matter domination

$$R_{eq} \approx 3.5 \times 10^{-5}(T_{2.7}{}^{4}/\Omega h^2) \;, \tag{1a}$$

$$T_{eq} \approx 6.8 \text{ eV } (\Omega h^2/T_{2.7}{}^{3}) \;, \tag{1b}$$

$$t_{eq} \approx 3 \times 10^{10}\text{sec } (\Omega h^2/T_{2.7}{}^{3})^{-2} \;, \tag{1c}$$

where $R(t)$ is the cosmic scale factor (normalized so that $R=1$ today), $2.7T_{2.7K}$ is the present temperature of the microwave background, $\Omega = \rho_{TOT}/\rho_{crit}$, $\rho_{crit} = 1.88h^2 \times 10^{-29}\text{g cm}^{-3} = 1.05 \times 10^4 h^2 \text{ eV cm}^{-3}$ is the critical density, and $H_o = 100h \text{ km sec}^{-1} \text{ Mpc}^{-1}$ is the Hubble parameter today. The initial data consist of: (i) the spectrum and type (adiabatic or 'isothermal') of density perturbations present; (ii) the amount of matter in the Universe (quantified by Ω); (iii) the composition of the matter--fraction (Ω_{baryon}) that is baryonic, fraction (Ω_{WIMP}) that is exotic Weakly-Interacting, Massive Particles (or WIMPs), etc. In principle, once armed with a possible set of initial data for the problem one can numerically simulate the formation of structure, and compare the results with the observed Universe to test the viability of those initial data. [For a recent review of numerical simulations of structure formation see White (1986a,b).] Until recently progress towards filling in the details of structure formation suffered severely from lack of knowledge of the initial data for the problem. Simply put, there was just too much phase space to explore!

The renaissance in cosmology initiated by the infusion of new ideas in theoretical particle physics has also revitalized the study of the formation of structure in the Universe. Preliminary forays into the very early Universe ($t < 10^{-2}$sec) have provided a number of important hints as to the initial data for the structure formation problem. Baryogenesis, the theory of the origin of the baryon number of the Universe, all but precludes the possibility of baryonic isothermal density perturbations (Turner and Schramm 1979; also see Barrow and Turner 1981; Bond, Kolb, and Silk 1982; and Kolb and Turner 1983). In addition to solving the homogeneity, isotropy, flatness, and monopole problems, the inflationary Universe scenario (Guth 1981, Linde 1982, and Albrecht and Steinhardt 1982) leads to calculable primordial density perturbations. Quantum fluctuations during inflation result in adiabatic perturbations with the Zel'dovich spectrum (Bardeen, Steinhardt, and Turner 1983, Hawking 1982, Starobinskii 1982, and Guth and Pi 1982) and in an inflationary Universe with axions, isothermal axion perturbations with the Zel'dovich spectrum also arise (Steinhardt and Turner 1983, Linde 1985, and Seckel and Turner 1985). A class of Grand Unified Theories (or GUTs) lead to the production of topological entities which are line singularities and are referred to as cosmic strings. The production of cosmic strings in the very early Universe leads to isothermal perturbations in the matter of a definite spectrum

'BEWARE OF THE DARK SIDE'

DARK MATTER CANDIDATES

(VERY EXOTIC CANDIDATES NOT LISTED)

FOR REFERENCE:

$\rho_{crit} \simeq 10^{-29} g\, cm^{-3} \simeq 10^{4} eV\, cm^{-3}$

$n_\gamma \simeq 400\, cm^{-3}$

$n_{baryon} \simeq 10^{-7}\, cm^{-3}$

NECESSARY FOR $\Omega_x = 1$

	WIMP	MASS	'ABUNDANCE'	BIRTH SITE	
	'INVISIBLE' AXION	10^{-5} eV	$10^{9}\, cm^{-3}$	10^{-30} sec	10^{12} GeV
	'LIGHT' NEUTRINO†	30 eV	$109\, cm^{-3}$	1 sec	1 MeV
SUSY ZOO	PHOTINO/GRAVITINO/ SIMPSON NEUTRINO/ MIRROR PARTICLE/ AXINO	keVs	$10\, cm^{-3}$	10^{-5} sec	300 MeV
SUSY ZOO	PHOTINO/SNEUTRINO/ HIGGSINO/GLUINO/ HEAVY NEUTRINO/ SHADOW MATTER	GeVs	$10^{-6}\, cm^{-3}$	10^{-4} sec	50 MeV
GUTs	SUPERHEAVY MAGNETIC MONOPOLE	10^{16} GeV ($\simeq 10^{-8}$ g)	$10^{-22}\, cm^{-3}$	10^{-34} sec	10^{14} GeV
VERY SPECULATIVE THEORIES	PYRGONs/MAXIMONs/ PERRY-POLEs/NEWTORITEs/ SCHWARZSCHILDs	$\gtrsim 10^{19}$ GeV ($\gtrsim 10^{-5}$ g)	$\lesssim 10^{-25}\, cm^{-3}$	10^{-43} sec	10^{19} GeV
	QUARK† NUGGETs	$\simeq 10^{15}$ g	$10^{-44}\, cm^{-3}$	10^{-5} sec	300 MeV
	PRIMORDIAL BLACK HOLEs†	$\gtrsim 10^{15}$ g	$\lesssim 10^{-44}\, cm^{-3}$	$\gtrsim 10^{-12}$ sec	$\lesssim$ TeV

NB. † SIGNIFIES A SPECIES KNOWN TO ACTUALLY EXIST

Figure 1 - A partial listing of dark matter candidates (or WIMPs) provided by modern particle theories. The abundance listed is the average cosmic abundance required to provide $\Omega = 1$. Note that if the WIMPs also provide the halo density their local abundance should be about a factor of 10^4 higher.

and amplitude. Cosmic strings have recently been reviewed by Vilenkin (1985).

Since primordial nucleosynthesis constrains the fraction of critical density contributed by baryons to be

$$0.014h^{-2} \leq \Omega_{baryon} \leq 0.035h^{-2}$$

and the inflationary Universe scenario (as well as other theoretical prejudices) strongly suggest that $\Omega = 1$, the early Universe seems to be telling us that most of the matter in the Universe is non-baryonic (which is not inconsistent with the fact that most of the matter in the Universe is dark). Of course one of the currently fashionable (and I believe very attractive) possibilities is that the constituents of the dark matter are relic WIMPs left over from the very hot, early epoch of the Universe. The early Universe and modern particle theories working together have provided a very generous list of candidates for the dark matter, most of them hypothetical particles and other hypothetical entities (for a partial listing, see Fig. 1).

This will be the focus of my article. To place the candidates in their proper context I will begin with a very brief and superficial review of modern particle theory. Next I will discuss the production of relic WIMPs in the early Universe. Although in many respects the various WIMPs are interchangeable, there are some very important differences, differences which bear on the details of structure formation and the possible detection of the cosmic reservoir of WIMPs which may surround us; this will be the focus of the next section. As if a Universe dominated by WIMPs is not exotic enough, I will go to discuss some very exotic solutions to the Ω problem (the discrepancy between theory and observation with regard to the value of Ω). I will conclude with some prognostications and summarizing remarks!

Let me end the introduction with a set of conversion factors and useful formulae. Every problem has it's natural set of units; for the early Universe it is the so-called natural units of particle physics where $\hbar = c = k_B = 1$. In this system, the fundamental unit is the GeV = 10^3 MeV = 10^6 keV = 10^9 eV, and

$$1\ \mathrm{GeV}^{-1} = 1.97 \times 10^{-14}\mathrm{cm}\ ,$$

$$1\ \mathrm{GeV}^{-1} = 6.58 \times 10^{-25}\mathrm{sec}\ ,$$

$$1\ \mathrm{GeV} = 1.16 \times 10^{13}\mathrm{K}\ ,$$

$$1\ \mathrm{GeV} = 1.77 \times 10^{-24}\mathrm{g}\ ,$$

$$G_{Newton} = 1/m_{pl}^2 \qquad (m_{pl} = \text{'planck mass'})$$

$$m_{pl} = 1.22 \times 10^{19}\mathrm{GeV}\ ,$$

$$1\ \mathrm{pc} = 1.5 \times 10^{32}\mathrm{GeV}^{-1}\ ,$$

$$1\ M_{\odot} = 1.1 \times 10^{57}\mathrm{GeV}\ ,$$

$$H_o = 2.2 \times 10^{-42}h\ \mathrm{GeV}\ .$$

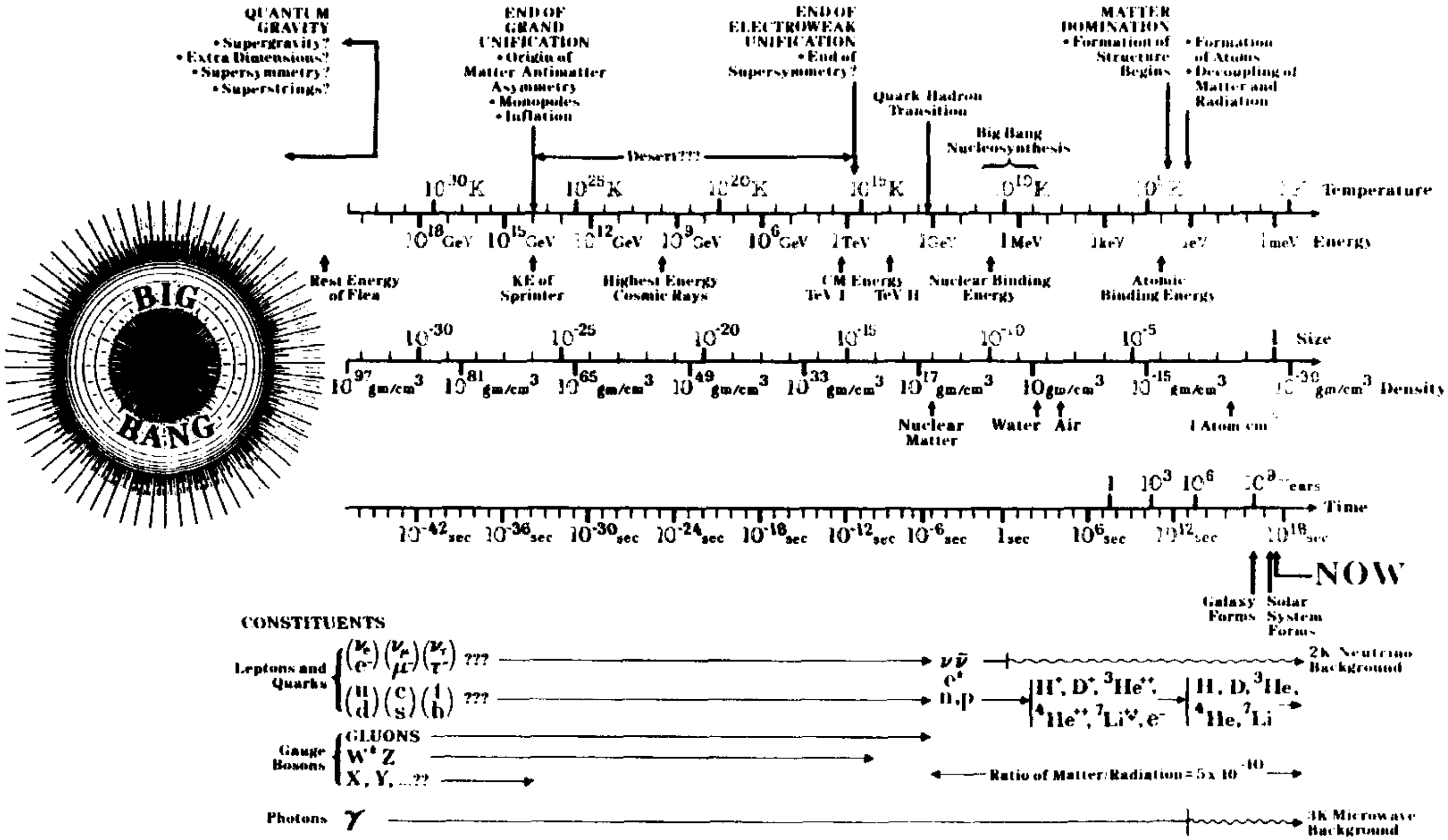

Figure 2 - The complete history of the Universe according to the standard hot big bang cosmology (also see the Figure in the Introduction to these proceedings).

During its earliest moments the Universe was radiation-dominated; i.e., for $t \lesssim 3 \times 10^{10}$sec $(\Omega h^2/T_{2.7}^3)^{-2}$. During this period the evolution of the cosmic scale factor R(t) and the temperature T are given by

$$R(t) \propto t^{1/2}, \tag{2a}$$

$$H = 1/2t = 1.66 g_*^{1/2} T^2/m_{pl} , \tag{2b}$$

$$T = 1.5 g_*^{-1/4} \mathrm{GeV}\ (t/10^{-6}\mathrm{sec})^{-1/2} , \tag{2c}$$

$$s = (2\pi^2/45)\ g_* T^3 , \tag{2d}$$

where g_* counts the total number of relativistic degrees of freedom (i.e., species with mass << T), and s is the entropy density of the Universe. The complete history of the Universe (according to the hot big bang model) is summarized in Fig. 2, as well as in the introduction to these proceedings.

2. 'FOUR TRANSPARENCY' COURSE IN MODERN PARTICLE THEORY

2.1 Their Standard Model

Particle physics has its standard model also. It is the SU(3)xSU(2)xU(1) gauge theory of the strong (or color), weak, and electromagnetic interactions. It is every bit as successful as the standard model of cosmology, providing an accurate and consistent description of elementary particle physics at energies of up to about 1000 GeV (corresponding to distances as small as about 10^{-17} cm!).

The fundamental constituents of matter are the quarks and leptons (see Fig. 3). Each quark flavor (6 are known: up, down, charm, strange, top, bottom) comes in three colors. [Color is a 3-dimensional charge to which the strong (or color) force couples.] The leptons are colorless. The color force is so strong that at low temperatures (T < few 100 MeV) the only finite energy configurations in the theory are 'colorless' -- quark-antiquark states known as mesons, triplets of quarks (one of each color) known as baryons, and the colorless leptons. The quarks and leptons seem to come in families -- a pair of quark flavors and a pair of leptons in each family or generation. So far three families have been discovered. At present there is no understanding of the number of families that exist, or how many should exist altogether. [Cosmology strongly suggests that there are less than or equal to 4 families (with light neutrinos) and the width of the recently discovered Z boson indicates that the number must be less than of order 10. See Schramm and Steigman (1985) for further discussion.]

Symmetry is a guiding principle in modern particle physics. The fundamental interactions of the quarks and leptons are described mathematically by an SU(3)xSU(2)xU(1) gauge theory, a theory based on the symmetry group SU(3)xSU(2)xU(1). In gauge theories particles exist in multiplets, members of which are related to each other by symmetry operations. The interactions are mediated by gauge bosons and the gauge bosons are the physical manifestations of the symmetry transformations.

The color force is described by the SU(3) part of the gauge group; the quarks come in color triplets (say, red, green, and blue); and there are 8 massless gauge bosons, called gluons, which mediate the color force and rotate one color quark into another (see Fig. 3). [Note the gluons themselves possess color and form an octet multiplet. The 'strong nuclear force' is now generally believed to be the residual color force felt between color neutral states, in analogy with the van der Waals force.]

In the standard model the electromagnetic and weak forces are unified in the framework of the so-called electroweak interaction, which is described by the SU(2)xU(1) part of the model. The particle multiplets are the quark and lepton 'flavor' pairs (or doublets), e.g., u-d and ν_e-e; the gauge bosons are the photon and W and Z bosons (which form a triplet of particles under SU(2)xU(1)). The unified electroweak theory is also known by the names of its inventors: The Weinberg-Salam-Glashow theory.

2.2 Hidden Symmetry (Spontaneous Symmetry Breaking, or SSB)

As you must well know the W and Z are not massless bosons, having masses of about 81 and 93 GeV respectively. How can that be in a unified gauge theory where their sibling the photon is massless? This brings us to one of the most fundamental ideas in modern particle physics, 'Hidden Symmetry' or SSB. The basic idea is that the theory possesses more symmetry than its solutions do. The theory does indeed have the full symmetry of SU(3)xSU(2)xU(1) in spite of the massive W and Z bosons. The full symmetry however is not possessed by the lowest energy solution or vacuum state of the theory.

In gauge theories the free energy (per unit volume) can be expressed in terms of one or more of the scalar fields which are also part of the theory (often called Higgs fields). The free energy $V_T(\phi)$ is often referred to as the effective potential or Higgs potential. At low temperatures the free energy is minimized by the Higgs field having a non-zero value (see Fig. 3). This vacuum expectation value (or vev) of the Higgs field(s) acts as an order parameter whose non-zero value signals SSB. In particular, the masses of the W and Z bosons are proportional to $\langle\phi\rangle$:

$$M_W,\ M_Z \simeq g\langle\phi\rangle$$

where g is the gauge coupling constant and $\langle\phi\rangle \simeq 300$ GeV. The vacuum state only possesses a U(1) symmetry, which corresponds to electromagnetism. At low temperatures the SU(2)xU(1) theory is said to be spontaneously broken to U(1). At high temperatures, finite temperature effects change the shape of the Higgs potential, so that its minimum occurs at $\langle\phi\rangle = 0$, and at high temperatures the full symmetry of the theory is restored (see Fig. 3).

The symmetry restoration temperature for the electroweak theory is about 300 GeV. While 300 GeV is a very high temperature by laboratory standards, such high temperatures (and up to 10^{19} GeV) should have existed during the earliest moments of the Universe. Thus spontaneously broken symmetries should have been restored in the early Universe, and

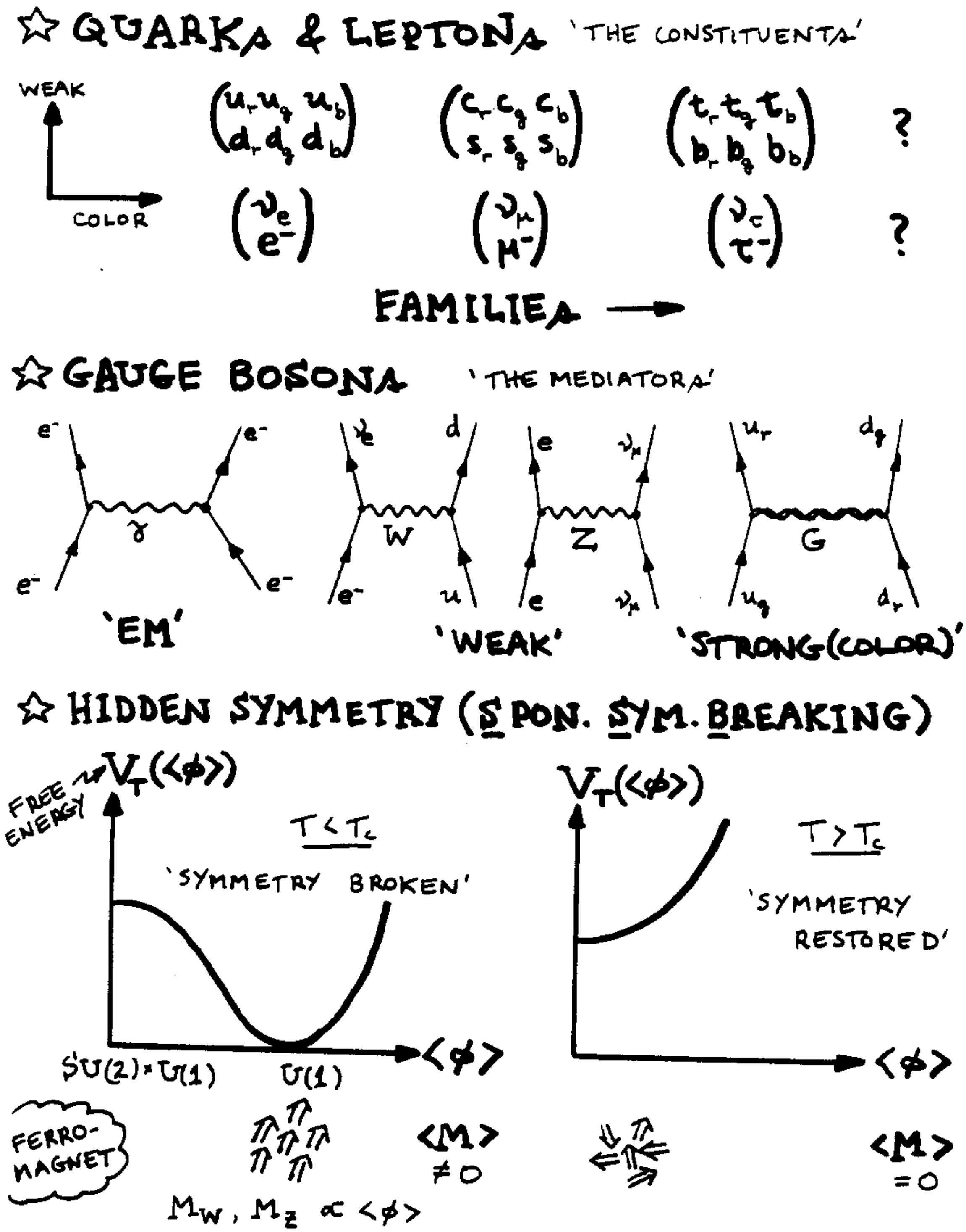

Figure 3 - Summary of key aspects of the standard model of particle physics, the SU(3)xSU(2)xU(1) gauge theory.

broken as the Universe cooled. SSB phase transitions then are a natural consequence of modern particle theory applied to the early Universe.

Analogous phenomena exist in more familiar settings. Consider a ferromagnet. The spin interactions of the individual atoms are described by Maxwell's equations, which of course possess rotational symmetry. However, at low temperatures, rotational invariance is no longer manifest as the lowest energy configuration of the system (spins aligned) does not possess rotational symmetry -- rotational symmetry has been spontaneously broken. At high temperatures (i.e., temperatures above the Curie temperature) the symmetry is restored as the spins are no longer aligned in the configuration with the minimum free energy.

2.3 Beyond the Standard Model--Why?

Their standard model then is a gauge theory which undergoes SSB

$$SU(3)xSU(2)xU(1) \xrightarrow[T_c \approx 300\,GeV]{} SU(3)xU(1) \,,$$

reflected in the fact that only the photon and gluons are massless and the fact that the weak force is very short-ranged ($r \approx M_W^{-1}$, $M_Z^{-1} \approx 10^{-16}$cm). Their standard theory is well supported by all the experimental data, which at present involves experiments done at energies $\lesssim$ 1000 GeV.

It is not without its shortcomings however. Although it is clear that a key feature of the theory is SSB, the scalar (or Higgs sector) of the theory is totally unexplored. No Higgs particles have been discovered. Indeed, these fields were put into the theory for the express purpose of SSB and to give quarks and leptons masses. [Owing to their expected masses and the weakness of their interactions, Higgs particles will only be accessible to experiments at the next round of new accelerators -- the Tevatron $p\bar{p}$ collider at Fermilab, the Stanford Linear Collider (or SLC) at SLAC, or perhaps not until the Superconducting SuperCollider (or SSC) is built.] While no Higgs particles have yet been discovered, almost all high energy theorists are confident that something like the Higgs mechanism must exist.

There are many indications in the standard model that there must be some more fundamental theory beyond the standard model. The theory is not truly unified in the sense that it is based upon a group which is a (direct) product of groups. There are too many particle multiplets and the quarks and leptons exist in separate multiplets. Because the quarks and leptons exist in separate multiplets there is no reason that their electric charges be related in a simple way (and of course we know that they are, the charge of the proton and of the positron are equal to a high degree of precision). The standard model casts no light on the values of quark and lepton masses or on why quarks and leptons come in families. Gravity is not included in the theory. There are many other more technical problems which also point to the fact that there must be something beyond the standard model.

Just as cosmologists suspect that something interesting must have happened during the first 10^{-2} sec after the bang, particle physicists strongly suspect that there must be a more fundamental theory which incorporates and goes beyond their standard model. With the exception of quark nuggets (stable, macroscopic aggregates of quark matter with nuclear density) the standard model of particle physics supplies no candidates for dark matter beyond ordinary baryons in some non-luminous guise (e.g., jupiters, primordial black holes, massive black holes, etc.). As we shall soon see virtually all the extensions of the standard model provide us with a generous supply of dark matter candidates. Next I briefly review some of the currently fashionable theoretical ideas in particle physics, emphasizing the dark matter candidates which are predicted (also see Fig. 3). Beware! My review does not do justice to these theoretical ideas. I refer the interested reader to the following very readable literature: Quigg (1983), Georgi (1984), Langacker (1980), Ramond (1983), Ross (1984), Green (1985), and Greenberg (1985).

2.4 Minimal Extensions of the Standard Model (or Messing with the Higgs Sector)

Since so little is known about the Higgs sector it seems like a natural place to start tinkering around. In the standard model there is one complex doublet of Higgs fields. By adding a triplet of Higgs which also develops a vev (albeit a very small one, $\langle\phi_{triplet}\rangle \lesssim$ MeV) Gelmini and Roncadelli (1981) constructed a model (the so-called 'majoron model') in which neutrinos have a (majorana) mass and additional interactions which violate lepton number (which is spontaneously broken in this theory). Other similar models exist. The new interactions which violate lepton number have all kinds of interesting astrophysical effects which have recently been reviewed by Kolb (1984).

Peccei and Quinn (1977) proposed adding one additional Higgs doublet to the theory, so that the theory would have an additional symmetry (now known as PQ symmetry) which is also spontaneously broken. Why would they do such a thing? [As you are beginning to see, symmetry is a guiding principle in modern particle theory. Since we only see a few symmetries at the energy scale at which we operate ($\lesssim$ TeV), essentially all the new symmetries introduced into the theory must be spontaneously broken!]

Although essentially all particle physicists believe that SU(3) or QuantumChromoDynamics (QCD) is the correct theory of the strong interactions, it has one, very bad problem: non-perturbative effects in the theory violate CP (charge conjugation combined with parity) and T (time reversal) invariance (leaving CPT intact) and should lead to an electric dipole moment for the neutron which is a factor of 10^9 or so larger than the present experimental limit (unless the non-perturbative effect is 'fine-tuned' away). The PQ symmetry solves this problem by effectively making the coefficient of the offending term in the Lagrangian a dynamical variable, whose potential has a minimum at a value where CP and T are very nearly conserved. Wilczek (1978) and Weinberg (1978) pointed out that the existence of such a broken symmetry would lead to a new, light psuedoscalar boson, which they dubbed the axion. The mass of the axion, its lifetime, and its coupling to ordinary matter are all determined by the symmetry breaking scale of the PQ symmetry, f_{PQ}.

$$m_a \approx 10^{-5}\text{eV}\ (10^{12}\text{GeV}/f_{PQ}) ,$$

Figure 4 - Guide to the theoretical ideas beyond the standard model of particle physics and the candidate WIMPs they predict.

$$\tau(a \rightarrow 2\gamma) \simeq 10^{41} \text{yrs} \, (f_{PQ}/10^{12}\text{GeV})^5 \; ,$$

$$g_{aee} \simeq m_e/f_{PQ} \qquad (g_{aee} = \text{coupling of the axion to } e^-)$$

Originally, Peccei and Quinn proposed that f_{PQ} be the same as the weak symmetry breaking scale (economy of scales so to speak). However such an axion (mass of a few 100 keV) was quickly ruled out by laboratory searches and astrophysical arguments. [Because of its short lifetime ($\simeq$ few sec) such an axion would not be of any interest as a dark matter candidate.] The requirement that the cooling of various kinds of stars by axion emission not be too efficient leads to a lower bound to f_{PQ} of about 10^8 GeV -- very far from the weak scale, but as we shall see cosmologically very interesting for $f_{PQ} \simeq 10^{12}$ GeV. The so-called 'strong CP problem' is solved regardless of the value of f_{PQ}. In fact, at present despite the lack of any experimental evidence for its existence, the axion remains the most attractive solution for this nagging problem.

2.5 Grand Unification

The first step towards unification of all the forces is the unification of the strong, weak, and electromagnetic forces, or so-called grand unification. Grand Unified Theories (or GUTs) are usually based upon a gauge group which is not a product of separate factors, and have quarks and leptons in the same multiplets. The simplest GUT is based upon the group SU(5), although its viability is in doubt as its prediction for the proton lifetime is about a factor of ten shorter than the present experimental lower limit (Perkins 1984). A multitude of other groups have been proposed including SO(10), E6, SO(18), and E8, to mention just a few.

Generically, GUTs makes several predictions: interactions which violate B and L (afterall quarks and leptons are in the same multiplets), the existence of stable, superheavy magnetic monopoles, and an additional scale of SSB, typically of order 10^{14} GeV. The gauge (and Higgs) bosons which mediate proton decay obtain masses of this order so that the processes which violate B and L are very, very weak, leading to a rather longlived proton, $\log(\tau_p/\text{yr}) \simeq O(30)$. Most GUTs also predict that neutrinos have small masses (much smaller than those of the other quarks and leptons and very often << 1 eV). Some GUTs also predict the existence of cosmic strings. I will discuss monopoles and cosmic strings again later. GUTs can also incorporate PQ symmetry and therefore axions. In fact grand unification provides another natural scale for f_{PQ}, the grand unification scale, or about 10^{14} GeV.

2.6 Supersymmetry/Supergravity (SUSY/SUGR)

Supersymmetry is the symmetry which interchanges fermions and bosons. In a supersymmetric theory there is a bosonic counterpart for every fermion and vice versa. We certainly see no evidence for such a symmetry in the world around us, e.g., there is no massless fermionic partner for the photon, or scalar partner for the electron. What is the motivation for supersymmetry then? Mathematically supersymmetry is very elegant, and it is the last symmetry one has available to invoke! In a more serious vein, when it is made a gauge symmetry (this is called supergravity), supersymmetry leads to a generally covariant theory, that is, it automatically incorporates general relativity into the theory. Thus it offers the hope of unifying gravity with the other forces. Supersymmetry also offers the hope of cleaning up a technical problem which all GUTs have in common: the discrepancy of the weak and GUT symmetry breaking scales, some 12 or so orders of magnitude in a typical GUT. Although one is free to set these scales to very different energies, quantum corrections spoil this, and tend to raise the weak scale up to the GUT scale (or the highest scale in the theory). Supersymmetry can be used to stabilize the discrepancy once it is initially set, "set it and forget it", so to speak.

Since we see no evidence of SUSY in our world it too must be a broken symmetry. In order to stabilize the weak scale, SUSY breaking must effectively occur at the weak scale. This means that the SUSY parnters, or spartners, of all the known particles must have masses of order the weak scale, where "of order" means between a few GeV and a TeV. The scalar partners of the quarks are called squarks; the scalar partners of the leptons are called sleptons; the fermionic partners of the photon, gluon, W, Z, and graviton are the photino, gluino, Wino, Zino, and gravitino respectively. The fermionic partners of the Higgs particles are known as Higgsinos.

Because of an additional symmetry that most SUSY/SUGR models have (called R-parity) the lightest spartner is stable. Because the effective SUSY breaking scale is of order the weak scale, the interactions of spartners with ordinary particles are about as strong as the usual weak interactions. This makes the lightest spartner (or LSP) an ideal candidate WIMP. In different models different spartners turn out to be the LSP; the most popular LSPs are the photino, sneutrino, and Higgsino. Typically, the LSP has a mass of order a few GeV.

GUTs can be supersymmetrized and in fact almost all SUSY/SUGR models are SUSY/SUGR GUTs. The unification scale in these theories is higher, more like 10^{16} GeV and these theories are supposed to describe physics at energies up to 10^{19} GeV. Therefore, SUSY/SUGR models also predict all the additional particles that GUTs do -- magnetic monopoles, massive neutrinos, axions, and cosmic strings (in some cases).

2.7 Kaluza-Klein Theories

Another approach to unification is through geometry (in analogy to general relativity). Indeed this approach dates back to work done by Kaluza, and Klein in the 1920's (and also caught Einstein's fancy). The basic idea of Kaluza-Klein theories is that space-time has more than the 3+1 (3 space, 1 time) dimensions that we are familiar with, say, 3+N space and 1 time dimensions. Space-time in these theories is supposed to be a 4-dimensional manifold cross an N-dimensional compact manifold which we haven't yet noticed (typical dimensions of the order of the planck length, 10^{-33} cm). The symmetries (more precisely, the isometries) of the compact manifold give rise to the gauge symmetries we observe in our 4 dimensions. The natural energy scale of these theories is 10^{19} GeV. In order to accommodate the gauge symmetry of the

SU(3)xSU(2)xU(1) model N must be ≥ 7. These theories need not necessarily incorporate grand unification (although that possibility is not precluded). Such theories predict the existence of stable planck mass objects, sometimes called pyrgons. In addition, these theories suggest that during its earliest history ($t < 10^{-43}$ sec), the Universe might have had all its 3+N space dimensions equally accessible. Of course one has to explain why the vacuum state of the theory has N space dimensions curled up (or alternatively, why 3 of the spatial dimensions are so large).

The concept of additional space-time dimensions has become increasingly popular in recent years (because all the physics of 4 dimensions has been done!), while the popularity of the Kaluza-Klein idea has waned. Although conceptually very attractive, there are many serious difficult problems, including incorporating chiral (particles whose right-handed and left-handed components have different interactions) fermions (the kind we know and love), keeping the compact dimensions compact, and constructing a quantum theory which is at least renormalizable.

2.8 Superstring Theories

Superstring theories incorporate every trick in the book -- gauge symmetry, supersymmetry, extra dimensions and one new one, strings. The basic idea is that the fundamental particles are not point-like, but rather are string-like, 1-dim entities. Such theories can only be consistently formulated in 10-dimensions with either the gauge group E8xE8' or SO(32).

Particle theorists are extremely excited about superstring theories as they unify all the forces of nature (including gravity) in a finite quantum theory and are almost unique (only five string theories are known to exist). [The usual gauge theories are not finite, but rather are only renormalizable, i.e., infinities can be consistently swept under the rug.] In principle, starting from the superstring (which describes physics at or above the Planck scale) one can calculate everything -- the masses of all the fermions, the GUT, etc.

When viewed at large distances the loops look like point-like particles (large distances here means large compared to the Planck length, 10^{-33} cm). The so-called point-like (or field theory) limit of a superstring theory is supposed to be a SUSY/SUGR GUT. All the WIMP candidates predicted by SUSY GUTs are also predicted by superstring theories.

If the symmetry group of the point-like theory is E8xE8', there is an interesting new possibility for dark matter. In this case there are two sets of particles, those whose interactions are described by E8 and those whose interactions are described by E8', which only interact with each other via gravity. Assuming that this is the case, at low energies one would have baryons, mesons, and leptons and their analogous (say, shadow) counterparts, alike in every respect, same masses, same interactions, etc, but only interacting with each other via gravity. Shadow matter is the perfect (but as it turns out also the perfectly implausible) candidate for the dark matter. [For further discussion of the shadow world see Kolb, Seckel, and Turner (1985).]

While particle physicists are very optimistic about the superstring (and rightfully so, a quantum theory of gravity which is finite, almost unique, and in principle predicts everything doesn't come along every day), solid results have been few and far between thus far.

Notice the progression of theoretical ideas here. GUTs are supposed to describe physics up to around 10^{14} GeV or so, SUSY/SUGR GUTs up to 10^{19} GeV, and superstring theories at energies above 10^{19} GeV.

2.8 Composite Models

Another, somewhat orthogonal, approach to going beyond the standard model involves the idea that many of the fundamental objects of the standard model, e.g., quarks, leptons, Higgs bosons, etc. are not fundamental, but rather are themselves made up of more fundamental entities, named variously as preons, rishons, etc. Indeed the number of quarks and leptons and their pattern of increasing masses suggests that they might actually be bound states of more fundamental objects. These models all face one fundamental difficulty: to have objects of a given size whose mass is much, much smaller than 1/size (i.e., have a Compton wavelength much bigger than their size; in all previous experience the reverse is true). Experiments indicate that the scale of compositeness (if there is one) must be greater than about a TeV. Various tricks (including chiral symmetry, the Nambu-Goldstone mechanism, and SUSY) have been used to keep the masses of the composite objects small compared to the scale of compositeness. A number of such theories have been proposed, including technicolor, the preon model, etc. Thus far none of them have proven to particularly elegant or compelling. Most of these theories predict some exotic, stable states which could be dark matter candidates.

2.9 'The Program'

The following is a brief summary of which theories predict which dark matter candidates.

Axion -- Simple extensions of the standard model, GUTs, SUSY/SUGR, Superstrings.

Massive neutrinos -- Simple extensions of the standard model, GUTs, SUSY/SUGR, Superstrings.

Spartners -- SUSY/SUGR, Superstrings

Monopoles and Cosmic Strings -- GUTs, SUSY/SUGR, Superstrings.

Quark Nuggets -- All of the above (potentially).

Pyrgons -- Models with extra dimensions.

3. THE PRODUCTION OF RELICS IN THE EARLY UNIVERSE

3.1 Hot and Cold Running WIMPs

Because the Universe was very hot during its earliest epoch, all kinds of interesting particles were present in great abundance. When the temperature of the Universe is >> the mass of a given species, that species (if in equilibrium) should be present in almost equal numbers as the photons,

$$n_x/n_\gamma = (g_{xeff}/2) ,$$

where g_{xeff} is 1(or 3/4) times the number of degrees of freedom (g_x) for a boson (or fermion). At temperatures << the mass of the species the equilibrium abundance relative to photons is exponentially small (assuming the species does not have a chemical potential)

$$n_x/n_\gamma \approx (\pi/8)^{1/2}(g_x/2\zeta(3))(m_x/T)^{3/2}\exp(-m_x/T) .$$

The abundance of a given species can only track its equilibrium abundance so long as the interactions which allow it to adjust its number per comoving volume (decays and annihilations) are occurring rapidly on the expansion timescale. For stable particles this means so long as the annihilation rate ($\Gamma \approx n_x(\sigma v)_{ann}$) is greater than the expansion rate H.

Once the annihilation rate drops below the expansion rate the number of particles per comoving volume remains constant. If this occurs while the species is still relativistic, its abundance relative to the photons freezes out at a value of order unity. Such relics are often referred to as hot relics. If this occurs when the species is nonrelativistic, its abundance relative to photons freezes out at a value much smaller than that of the photons. Such relics are often referred to as cold relics.

The freeze-out temperature (T_f) depends upon the annihilation cross section and is given by

$$x_f \equiv m_x/T_f \approx \ell n[(n+1)a\lambda] - (n+1/2)\ell n[\ell n[(n+1)a\lambda] , \tag{3a}$$

$$a = 0.15(g_x/g_*) , \tag{3b}$$

$$\lambda = 0.264\, g_*^{1/2}\, m_{pl}\, m_x(\sigma v)_o , \tag{3c}$$

where the annihilation cross section has been parameterized by

$$(\sigma v)_{ann} = (\sigma v)_o(T/m_x)^n.$$

Since entropy per comoving volume remains constant (assuming the expansion is isentropic), the number of WIMPs per comoving volume is simply proportional to Y, where

$$Y = n_x/s$$

and s is the entropy density of the Universe ($\simeq 0.44 g_* T^3$). The final abundance Y_{final} is determined by when the annihilations freeze out.

For hot relics, $x_f \ll 3$ ($T_f \gg m_x$) and

$$Y_{final} \simeq 0.278\ (g_{xeff}/g_*). \tag{4}$$

On the other hand, for cold relics $x_f \gg 3$ ($T_f \ll m_x$) and

$$Y_{final} \simeq (n+1)x_f^{n+1}/\lambda\ . \tag{5}$$

Since the entropy density today (photons and 3 neutrino species) is about 7.04 times the number density of photons

$$(n_x/n_\gamma)_{today} \simeq 7.04\ Y_{final}\ .$$

The contribution of a given relic species to Ω is then

$$(\Omega_x h^2/T_{2.7}^{\ 3}) \simeq 2.67 \times 10^8 (m_x/\mathrm{GeV})\ Y_{final}\ . \tag{6}$$

[For further details and references see, Scherrer and Turner (1986).]

Light neutrinos ($\lesssim$ few MeV) with the usual weak interactions freeze out when they are still relativistic and so are hot relics, with

$$(n_{\nu\bar{\nu}}/n_\gamma)_{today} = 3/11\ , \tag{7a}$$

$$(\Omega_\nu h^2/T_{2.7}^{\ 3}) \simeq m_\nu/96\mathrm{eV}. \tag{7b}$$

For heavy neutrinos ($\gtrsim$ few MeV), the annihilation cross section is of the order $G_F^2 m_\nu^2$, so that $x_f \simeq 20$ ($T_f \simeq m_\nu/20$), and so they are cold relics with

$$(\Omega h^2/T_{2.7}^{\ 3}) \simeq (m_\nu/2\mathrm{GeV})^{-1.9} \tag{8}$$

(Lee and Weinberg 1977).

For the lightest spartner (LSP), the annihilation cross section depends upon the masses of the other spartners. Because all the spartner masses are typically of the order of the weak scale, the annihilation cross section is also of the order of $G_F^2 m_{LSP}^2$, implying that the LSP will also be a cold relic, with Ω_{LSP} given by a formula similar to that for a heavy neutrino. [For further discussion see Ellis etal. (1984).]

3.2 Topological Relics (Monopoles and Cosmic Strings)

In spontaneously broken gauge theories there are, in addition to the fundamental particles of the theory, topological entities, monopoles, strings, and domain walls. These objects correspond to classical configurations of the gauge and Higgs fields. Let me be a little more specific.

In general the Higgs field has many components and the minimization of the free energy may not uniquely specify all the components. Say for instance that the magnitude of the Higgs field is specified, but not the direction of the Higgs field in group space. In this case there will be a set of Higgs field values which minimize the free energy, but differ in the direction they point in group space (they comprise the vacuum manifold). Consider the possible ways that the Higgs field can be laid out in physical space. One way is for the Higgs field to be laid out uniformly (boring!). Another way is to be laid out in different directions in different places in physical space as in Fig. 5. In the configuration shown in Fig. 5a the Higgs field must necessarily vanish at a point. This configuration corresponds to a stable, magnetic monopole. The energy associated with the configuration (part in potential energy as ϕ deviates from the minimum at the center and part in magnetic field energy) is

$$m_M = M/\alpha ,$$
$$\simeq 10^{16}\text{GeV } (M/10^{14}\text{GeV}) ,$$

where $\alpha = g^2/4\pi$, g is the gauge coupling constant (typically $\alpha \simeq 10^{-2}$) and M is the symmetry breaking scale. The size of the region where ϕ vanishes is of order M^{-1}, i.e., the monopole is not point-like, but has a finite size. In configuration 5b, there is necessarily a line along which ϕ vanishes; this object corresponds to a cosmic string. The width of the string is of order M^{-1} or 10^{-28}cm (10^{14}GeV/M) and the mass per unit length is of order M^2 or 10^{18}g cm^{-1} $(M/10^{14}\text{GeV})^2$.

Whether or not a given gauge theory has monopole or string solutions depends upon the structure of the vacuum manifold. Whenever a semi-simple group (i.e., a group without an explicit U(1) factor) breaks down to a group with an explicit U(1) factor monopole solutions exist. Since we know that the 'low energy' (low here means of order a TeV or so) group is SU(3)xSU(2)xU(1), which has an explicit U(1) factor, any GUT based upon a semi-simple group will have monopole solutions. Thus monopoles are a very generic prediction of GUTs.

The condition to have string solutions is that the group which the theory breaks down to must have a discrete symmetry. Some, but certainly not all GUTs have this feature. [There are also topological configurations which correspond to two-dimensional sheets where ϕ vanishes; these are called domain walls. Walls are cosmologically disastrous. For further discussion of all of these topological objects, see Vilenkin (1985).]

The primary way that topological objects are produced is via the so-called Kibble (1976) mechanism during a SSB phase transition. Recall that at high temperatures symmetries are restored; as the Universe cools below the critical temperature for a given SSB transition ($\simeq$ M) the Higgs field takes on a non-zero vev. The standard cosmology has particle horizons ($d_H \simeq ct$) and so causality prevents any physical process from operating on scales greater than order the horizon distance. Clearly the Higgs field cannot become correlated on scales larger than the particle horizon (and often the microphysics sets an even smaller correlation scale). If the theory permits such configurations, of the order of 1 monopole or string will be formed per horizon volume just due to the fact that the Higgs field cannot be correlated on larger scales (see Fig. 5).

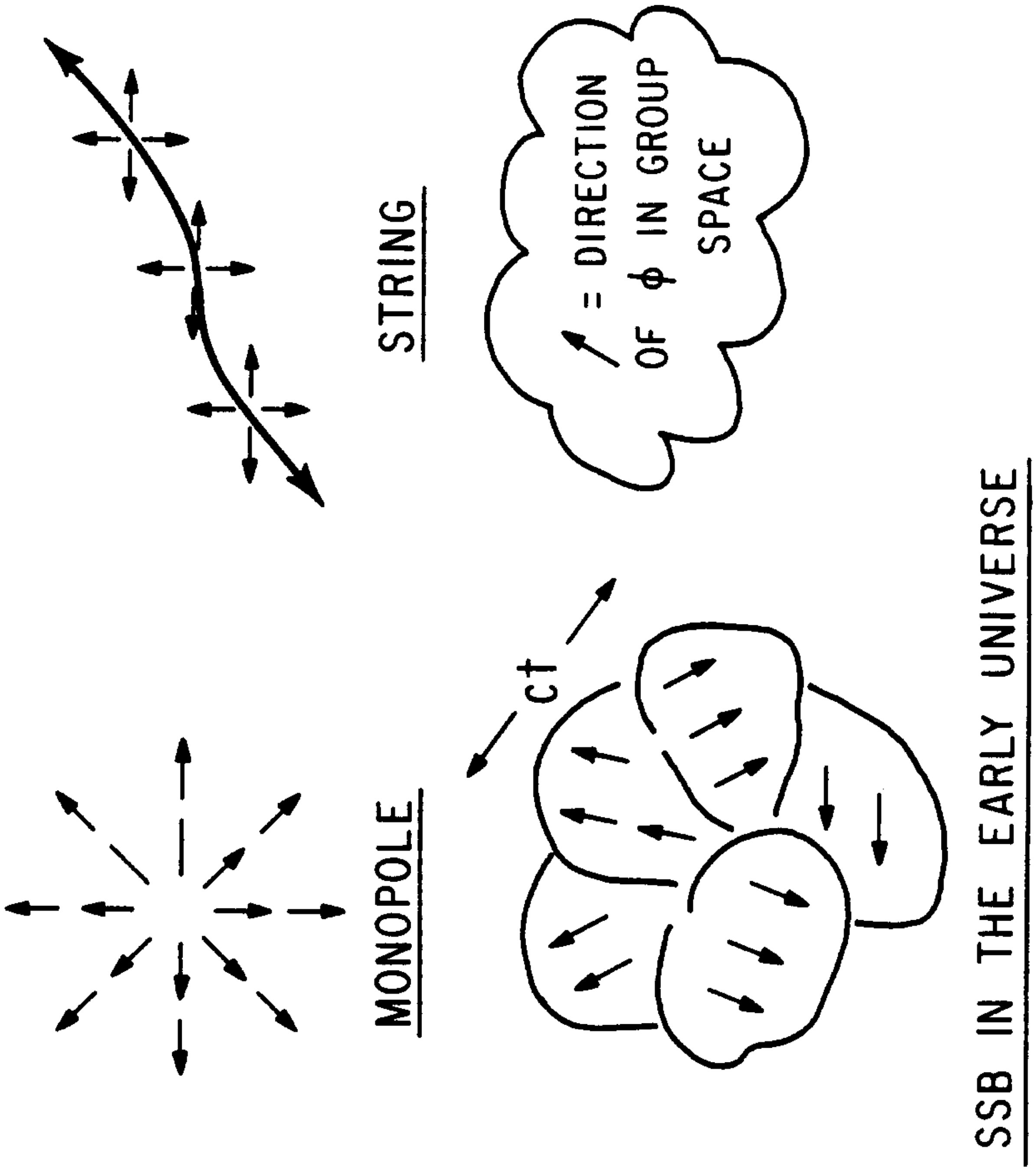

Figure 5 – Schematic representation of two of the topological objects predicted by GUTs, the monopole and cosmic strings, and their production by the Kibble mechanism in the very early Universe. These objects correspond to non-trivial configurations of the Higgs and gauge (not shown) fields. Because of the existence of particle horizons in the early Universe, of order 1 of these topological objects is produced per horizon volume during SSB.

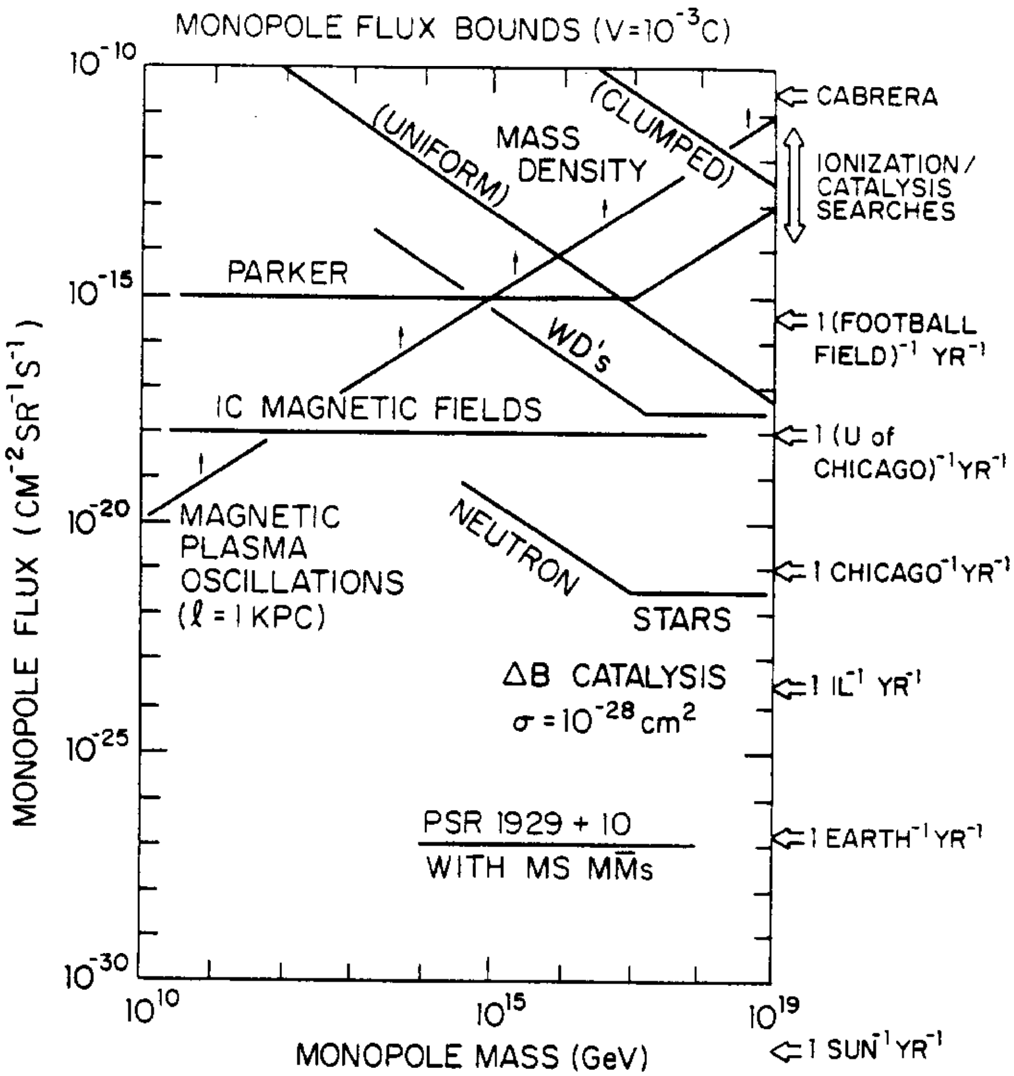

Figure 6 - A summary of the astrophysical and cosmological bounds to the local flux of superheavy magnetic monopoles (from Turner 1986b).

For the monopole and the usual GUT scale of 10^{14} GeV, this leads to a disastrous overproduction, so many monopoles that the Universe would reach a temperature of 3 K at the tender age of 30,000 years! If the overproduction can be avoided (e.g., by a complicated symmetry breaking pattern, or by inflation followed by thermal pair production or production at a much later phase transition) monopoles could possibly be a viable dark matter candidate. Of course the relic monopole abundance is also severely constrained by various astrophysical arguments, especially if they catalyze nucleon decay (see Fig. 6). The lack of any sensible theoretical guidance as to their primordial abundance and the very stringent astrophysical constraints on their relic abundance make monopoles a less than attractive dark matter candidate. [For a recent review of magnetic monopoles see Preskill (1984) or Turner (1986).]

While cosmic strings do not behave like relic particles (e.g., they eventually cut themselves, forming loops which can evaporate by the emission of gravitational waves as they oscillate), they can move matter around and induce isothermal perturbations with unusual properties. For $M \approx 10^{16} - 10^{17}$ GeV, cosmic strings may be able to trigger a viable scenario for structure formation and offer an intriguing alternative to the scenario of a WIMP-dominated Universe with adiabatic perturbations with the Zel'dovich spectrum (for further discussion see Vilenkin 1985).

3.3 Quark Nuggets

In a very interesting and thought-provoking paper Witten (1984) raised (and also all but dismissed) the possibility that the Universe could be baryon-dominated and flat ($\Omega = 1$). He supposed that for very large baryon number (>> 100) the stable configurations of matter were quark matter rather than nuclear matter (at present there is no evidence for this supposition).

He then investigated the formation of big globs of quark matter (hereafter referred to as quark nuggets) during the quark/hadron transition ($t \approx 10^{-5}$ sec, $T \approx 200$ MeV). He concluded that were it not for the fact that cooling is a very efficient process in the primordial plasma, most of the quarks in the Universe might have formed into quark nuggets of size 0.1÷100 cm and nuclear density, leaving only about 10% of the quarks in the form of free nucleons. Since quark nuggets would presumably not have participated in primordial nucleosynthesis, one could have $\Omega_{baryon} = 1$, with 0.1 in free nucleons and 0.9 in nuggets. The formation of nuggets has been studied further, by Degrand and Kajantie (1984) and very recently by Applegate and Hogan (1985) and Alcock and Farhi (1985), who all also conclude that quark nuggets are not a very likely candidate for the dark matter (although they could possibly have some interesting effects on primordial nucleosynthesis).

3.4 Cosmic Harmonic Oscillations (AKA Axions)

I have already discussed the motivation for the axion, now I will discuss how cosmic axions come into being. For the allowed values of the PQ symmetry breaking scale ($f_{PQ} \gtrsim 10^8$ GeV) axions interact so weakly that they should never have been in thermal equilibrium. They are however produced in another very novel and interesting way (see Fig. 7).

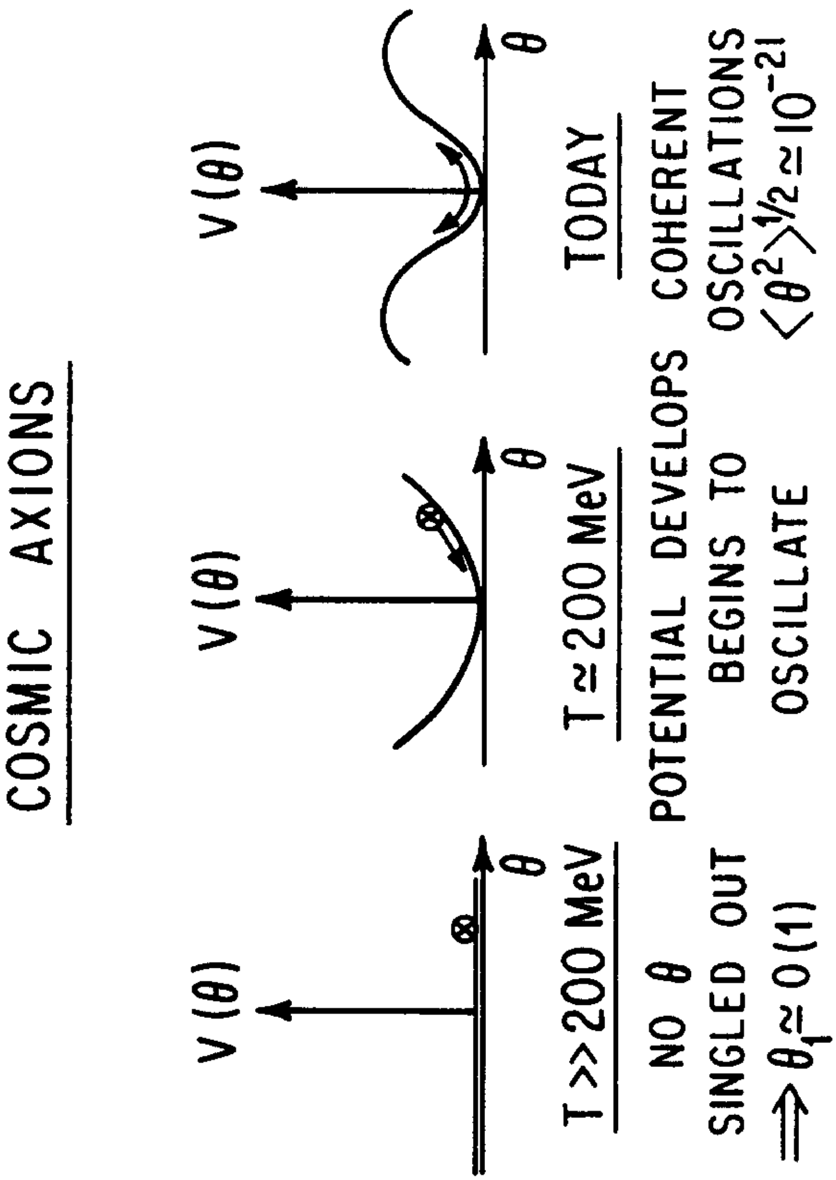

Figure 7 - Thermal history of the axion potential, V(θ). At high temperatures (f_{PQ} >> T >> few GeV) the potential is flat and no value of θ is preferred. At low temperatures (T ≈ few GeV) the potential develops a minimum due to instanton effects. Because of its initial misalignment, θ begins to oscillate. These oscillations have an amplitude of about 10^{-21} today and correspond to a condensate of very cold axions.

Denote the axion degree of freedom as θ and its potential as $V(\theta)$. At low temperatures (<< GeV) $V(\theta)$ is periodic and has its minimum at θ = 0 (the CP and T conserving minimum). The axion's potential develops due to non-perturbative QCD effects (so-called instanton effects). These non-perturbative effects vanish at high temperatures (T >> GeV). That is at high temperatures, the axion potential is flat and has no minimum (and the axion is massless).

Now let's follow the birth of the cosmic axions. At temperatures much greater than a few GeV, but below the PQ symmetry breaking scale, the PQ symmetry is broken but there are no dynamics to determine θ since its potential is flat. Denote its initial value by θ_1. There is no reason that θ_1 should be 0; in general, one would expect it to be of order unity, i.e., misaligned with the soon-to-be-determined minimum of its potential. Due to this initial misalignment, once the potential does develop (when non-perturbative QCD effects become important, $T \simeq O(\mathrm{GeV})$), θ will begin to oscillate. These cosmic coherent, classical oscillations of θ have energy density associated with them. In fact they behave just like NR matter. From the particle point-of-view they correspond to a condensate of very cold (NR) axions.

The energy density in these oscillations can and has been calculated by Preskill, Wilczek, and Wise (1983), Abbott and Sikivie (1983), Dine and Fischler (1983), and Turner (1986):

$$(\Omega_a h^2/T_{2.7}^3) \simeq 1.0(f_{PQ}/10^{12}\mathrm{GeV})^{1.18}(N/6)^{0.83}\theta_1^2 \ , \qquad (9)$$

here N is an integer which depends on precisely how the PQ symmetry is implemented (in the simplest models N = 6). Note that Ω_a increases with f_{PQ} and depends on the square of the initial misalignment angle, θ_1. If the Universe never inflated or inflated before PQ symmetry breaking, then it is the RMS value of θ_1, $\theta_{1RMS} = (\pi/N)/\sqrt{3}$, which should be used (when the oscillations commence, θ_1 is uniform on the scale of the horizon, but is uncorrelated on larger scales). In the inflationary case, θ_1 takes on different values inside different bubbles (or fluctuation regions), so that we do not know what value θ_1 takes on within our bubble (of course, averaged over all bubbles $\theta_{1RMS} = (\pi/N)/\sqrt{3}$). For $\theta_1 = \theta_{1RMS}$, $\Omega_a = 1$ requires a PQ breaking scale of about 10^{12}GeV, corresponding to an axion mass of about 10^{-5}eV.

3.5 Dark Matter and a New Dimensionless Number

As physicists we are all aware of the importance of dimensionless numbers. There are already a handful of important dimensionless numbers in cosmology, the net baryon number to entropy ratio ($n_B/s \simeq 10^{-10}$), the fractional primordial abundances of the light elements (D, ^{3}He, ^{4}He, ^{7}Li), the horizon crossing amplitudes of adiabatic density perturbations, to mention a few. For the first two we believe that we have a fundamental understanding of their origin, and with the inflationary scenario we may be on the way to understanding the third. Martin Rees has emphasized the existence of yet another dimensionless number if the Universe is not baryon-dominated. That number is the ratio of mass density in ordinary baryonic matter to that in exotic matter. If we adopt Ω = 1 and Ω_{baryon} = 0.1, then this ratio r is about 0.11.

Is this a significant dimensionless number whose eventual understanding may provide us with a new insight to the Universe and the laws of nature? Why is its value so close to order unity and not say 10^{-30} or 10^{30}? Is it yet another example of the anthropic principle at work (God forbid!)? If quark nuggets are the dark component, then a value of about 0.1 arises quite naturally: it is the fraction of quarks that remain free, which based upon simple physics Witten (1984) estimated to be of order 0.1. In this case there is good reason for r to be of order unity.

What about the other dark matter candidates? According to the very attractive scenario of baryogenesis the net baryon number to entropy ratio evolved during the very early history of the Universe due to non-equilibrium interactions which violate B, C, CP (for a recent review, see Kolb and Turner 1983). The baryon to entropy ratio which evolves can be written as

$$n_B/s = \varepsilon/g_* \ (10^{14}\mathrm{GeV\ or\ so}) \qquad (10)$$

where ε parameterizes the C, CP violation and must, based upon very general arguments be less than about $(\alpha/\pi) \simeq 10^{-3}$.

Now let's consider the relic abundance of a WIMP whose annihilations proceed via an interaction with roughly the strength of the weak interactions (e.g., a heavy neutrino, photino, sneutrino, Higgsino, etc.). The ratio of its relic abundance to the entropy density is given by Eqn. (5):

$$(n_X/s) \simeq x_f/(0.15 g_*^{-1/2} m_{pl} m_{WIMP} (\sigma v)_o) \qquad (11)$$

where $n = 0$, and $x_f \simeq O(20)$ depends logarithmically upon $(\sigma v)_o$, etc. This together with the baryon to entropy ratio allows us to calculate Martin Rees's ratio r

$$r = 0.15\ \varepsilon\ g_*^{-3/2}\ m_{pl} m_{nuc} (\sigma v)_o / x_f \ . \qquad (12)$$

For simplicity, if we take the WIMP mass to be of order m_{nuc}, $(\sigma v)_o \simeq G_F^2 m_{WIMP}^2$, $x_f \simeq 20$, $g_* \simeq 100$, and $\varepsilon \simeq 10^{-4}$, then the ratio r is just

$$r \simeq 10^{-9} m_{nuc}^3 m_{pl}\ G_F^2 \ . \qquad (13)$$

That r be of order unity (and not say $10^{\pm 30}$ then requires a large discrepancy between the weak scale ($G_F \simeq \langle\phi\rangle^{-2} \simeq 10^{-5}\mathrm{GeV}^{-2}$, where $\langle\phi\rangle \simeq 300$ GeV is the Higgs vev and sets the weak scale) and the scale of particle masses relative to the planck scale ($\simeq 10^{19}$ GeV).

Now consider the case of relic axions. Using Eqn. (9) it is straightforward to compute Martin Rees' ratio r:

$$r \simeq 0.1\ \varepsilon\ g_*^{-1/2}\ (m_{pl}/f_{PQ})^{1.2} \theta_1^{-2} \ . \qquad (14)$$

From this expression for r it is clear that in order to have r be of order unity, the PQ symmetry breaking scale shouldn't differ from the planck scale by too many orders of magnitude. Put another way, it means that f_{PQ} of the order of the GUT scale results in r of order unity, whereas $f_{PQ} = 300$ GeV results in $r \simeq 10^{-17}$ (assuming that the axion were stable for such a value of f_{PQ}).

Is there any significance to these relations or to the Martin Rees' ratio r? I don't know. In the case of quark nuggets, however, it is clear that r is quite naturally of order unity. In the other two cases, r being of order unity can be traced to relationships between fundamental scales in particle physics.

4. IMPLICATIONS

Although in many regards the different WIMP candidates are interchangeable, there are several important differences -- how they process primeval adiabatic density perturbations, the scales upon which there is enough phase space for them to cluster, and the prospects for their detection. I will summarize those differences here.

4.1 Freestreaming WIMPs

It has long been realized that density perturbations in a self-gravitating fluid in which the mean free path of the fluid constituents is finite will undergo Landau damping. For WIMPs, this effect is particularly severe as they are always effectively collisionless. Until the Universe becomes matter-dominated and WIMP perturbations can start to grow via the Jeans instability, perturbations can be damped by freestreaming of the WIMPs out of the perturbations. Following Davis, Lecar, Pryor, and Witten (1981) one can define the characteristic freestreaming scale

$$\lambda_{FS} = \int_0^{t_{eq}} v(t')dt'/R(t') \ . \tag{15}$$

Physically, λ_{FS} is the comoving distance that a WIMP could have traveled since the bang. Most of the contribution to the integral arises during the epoch when the WIMPs are relativistic (once they become NR, $v \propto R(t)^{-1}$ and λ only grows logarithmically). Clearly, λ_{FS} defines the characteristic damping scale for primeval perturbations: WIMP perturbations on scales smaller than the scale λ_{FS} will be strongly damped by the streaming of WIMPs out of the overdense regions and into the underdense regions. Careful calculations of the damping effects of collisionless WIMPs have been performed by Bond and Szalay (1983), Bond, Szalay, and Turner (1982), Peebles (1982), and Blumenthal and Primack (1984).

Assuming that the Universe is WIMP-dominated and flat, and that the WIMPs are characterized by a temperature T_{WIMP} (which is not necessarily the same as the photon temperature T), it is straightforward to compute λ_{FS}:

$$\lambda_{FS} \simeq 1 \text{ Mpc } (1\text{keV}/m_{WIMP})(T_{WIMP}/T) \times \tag{16}$$
$$[1 + \ln\{6(m_{WIMP}/\text{keV})^{1/2} (T/T_{WIMP})^{1/2}\}]$$

Note that for heavy WIMPs the damping scale is smaller; this is because they become NR earlier during the history of the Universe and hence cannot stream as far. The Table below shows the damping scale for a few of the dark matter candidates.

WIMP	MASS	T_{WIMP}/T	λ_{FS}(Mpc)
Neutrino	light	$(4/11)^{1/3}$	40 Mpc/(m/30eV)
Axion	10^{-5}eV	$< 10^{-14}$	$< 10^{-5}$Mpc
Axino/RH Neutrino/Light Gravitino	keV	1/4	1 Mpc
Heavy Neutrino/ LSP	GeV	1	10^{-5}Mpc

The scale 1 Mpc corresponds to a galactic scale. The relationship of λ_{FS} to the galactic scale neatly divides the WIMPs into three categories: (i) Cold, $\lambda_{FS} << 1$ Mpc -- the characteristic damping scale is much smaller than a galactic scale, and galactic-sized perturbations survive freestreaming; (ii) Warm, $\lambda_{FS} \approx 1$ Mpc -- the characteristic damping scale corresponds to a galactic scale; (iii) Hot, $\lambda_{FS} >> 1$ Mpc -- only perturbations on scales much larger than a galactic scale survive freestreaming. Almost all of the WIMPs fall into the category of cold dark matter. Only the neutrino is a hot WIMP. At present there are a couple of warm dark matter candidates -- a 1 keV gravitino, 1 keV right-handed neutrino, or a 1 keV axino (supersymmetric partner of the axion).

By far the damping effect of the WIMPs on the primordial spectrum of adiabatic density perturbations is the most important implication of the different candidates on structure formation. The damping mass determines which structures form first: for cold and warm WIMPs it's galactic-sized objects or smaller; for hot WIMPs it's very large structures (superclusters).

4.2 The Tremaine-Gunn Constraint

In a very nice paper Tremaine and Gunn (1979) discussed a kinematical constraint on dark matter candidates. In brief, they pointed out that for a gravitationally-bound system characterized by mass M, velocity dispersion σ, and size r, there is only so much phase space available

$$\mathcal{V}_{ph.sp.} \approx f\, \mathcal{V}_x\, \mathcal{V}_p/(2\pi)^3 \approx f m_{WIMP}^3\, \sigma^3\, r^3 \qquad (17)$$

where f is the possible quantum occupancy of each state. For fermions, f is at most the number of spin degrees of freedom; in fact, this is true for any particle which decouples while still in thermal equilibrium. Based on the amount of phase space available it follows that there is a maximum to the mass in WIMPs such a system can have

$$M_{max} \simeq m_{WIMP} \mathcal{V}_{ph.sp.} \approx f m_{WIMP}^4 \sigma^3 r^3 , \tag{18}$$

For all the WIMPs, except axions which are born with a very high quantum occupancy ($\gtrsim 10^{52}$!), f is of order unity. Eqn. (18) then implies a constraint on the minimum WIMP mass required such that the system could be WIMP-dominated. Taking f $\approx$ 2, the Tremaine-Gunn bound is

$$\begin{aligned} m_{WIMP} &\geq 100\text{eV}\,(100\ \text{kms}^{-1}/\sigma)^{1/4}\,(1\text{kpc}/r),^{1/2} \\ &\gtrsim O(5\text{eV}) \quad \text{Rich cluster ,} \\ &\gtrsim O(10\text{eV}) \quad \text{Small Group ,} \\ &\gtrsim O(30\text{eV}) \quad \text{Healthy-sized Galaxy ,} \\ &\gtrsim O(150\text{eV}) \quad \text{Dwarf Galaxy.} \end{aligned}$$

Only for the neutrino is the constraint interesting (recall because of their high quantum occupancy, these bounds do not apply to axions), and only for small systems, such as dwarf galaxies. If dwarf galaxies are WIMP-dominated and characterized by the parameters used to obtain the above bound, then neutrinos cannot be the dark matter (at least in dwarf galaxies), based upon kinematical grounds alone. [Madsen and Epstein (1985) have recently reexamined this constraint in light of better determinations of σ and r.]

The Tremaine-Gunn constraint is basically a kinematical constraint. If the mass of a WIMP exceeds their bound for a given system, that does not guarantee that such systems are WIMP-dominated -- that is a question of dynamics, it merely implies that it is kinematically possible.

4.3 The Search for WIMPs

From the above discussion, it is apparent that many of the WIMPs (essentially all the cold ones) have identical implications for structure formation, and therefore cannot be distinguished on that basis alone. Until recently, it was generally thought that in spite of the great reservoir of WIMPs in which we are swimming (see Fig. 1 and remember for WIMPs which cluster with galaxies the local density is about a factor of 10^4 or so higher) it would be impossible to detect their presence because of the feebleness of their interactions. It now appears that this pessimism was somewhat premature. A number of very clever ideas have been proposed for detecting the presence of WIMPs in the halo of our galaxy. I will briefly summarize this very exciting work.

Axions -- If axions are the halo dark matter, then their local number density is enormous, 3×10^{13} or so cm^{-3}. Sikivie (1983) proposed an idea which exploits the axion coupling to 2 photons to convert halo axions into photons. Because of this coupling, in the presence of a strong, inhomogeneous magnetic field axions will convert to photons. Because the halo axions are very NR ($v/c \simeq 10^{-3}$) the width of the line should be very narrow ($\Delta\lambda/\lambda \simeq 10^{-6}$). In a large high-Q, microwave cavity these photons might be detectable. Several groups are designing and/or building experiments based upon Sikivie's idea.

WIMP Heat -- In a very interesting paper, Goodman and Witten (1985) discussed the possibility of using supercooled, ultra-low heat capacity bolometric detectors to detect the small amount of energy (of order keV) deposited by a variety of WIMPs (photinos, sneutrinos, heavy neutrinos) when they interact in matter. A 10 kg detector operating at a temperature of order a few milliKelvin would register a count or so per day (depending upon the couplings of the WIMP). Drukier, Freese, and Spergel (1985) have followed up this idea in more detail. Cabrera etal. (1985) have proposed a bolometric detector which may be suitable for this purpose.

WIMP Annihilations -- If the dark matter in our halo is photinos, sneutrinos, Higgsinos, or heavy neutrinos, then WIMPs are annihilating all about us ($\langle\sigma v\rangle_{ann} \approx 10^{-26}$ cm^3 sec^{-1}) and some of the annihilation products may be detectable. Silk and Srednicki (1984) discussed the possibility that photino annihilations in the halo might produce enough low-energy antiprotons to explain the anomalously high flux of low energy antiprotons detected by Buffington and Schindler (1981). Stecker etal. (1985) have gone a step further and calculated the expected spectrum of antiprotons for this scenario.

Press and Spergel (1985) have pointed that the sun will capture significant numbers of WIMPs if the halo is WIMP-dominated, and Olive and Silk (1985) have discussed the possibility that neutrinos and antineutrinos produced by WIMPs annihilating in the sun might be detectable in large, underground detectors (such as those used to search for proton decay). Freese (1986) and Krauss, Srednicki and Wilczek (1985) have pointed out that the annihilations of those WIMPs captured by the earth might also be detectable in large, underground detectors.

In a very recent paper Srednicki, Theisen, and Silk (1986) have proposed an even more intriguing way of detecting WIMP annihilations in the halo, through the gamma ray lines they produce when they annihilate into a bound quark-antiquark state (such as ψ/J, T, etc.) and a monoenergetic photon. Photinos, sneutrinos, heavy neutrinos, and Higgsinos in the halo could be directly detected this way. Furthermore, if such gamma ray lines are detected, not only could the mass of the halo WIMPs be directly determined, but also the mass distribution of the halo could be probed by the directional dependence of the strength of the line (Turner 1986).

Monopole searches -- A variety of induction and energy loss searches are presently ongoing (for a recent review, see Groom 1986). Unfortunately, there has been no additional confirming evidence for the famous Valentine's Day event of 1982. The current level of sensitivity is about 10^{-13} cm^{-2} sr^{-1} sec^{-1}, and experiments are being designed and constructed at the sensitivity level of 10^{-16} cm^{-2} sr^{-1} sec^{-1}, which is a factor of 10 below the Parker bound (for monopoles lighter than 10^{17} GeV). Needless to say the discovery of monopoles as the dark matter would not only be a boon to astrophysicists, but also to particle physicists as it would be a confirmation of the idea of grand unification and to early Universe cosmologists as they would represent relics from the earliest moments of the Universe ($t \lesssim 10^{-34}$ sec).

Laboratory experiments -- Many of the dark matter candidates could have their existence confirmed in the laboratory. For example, spartners may be produced at the CERN Sp$\bar{p}$S collider (although they have not yet), the Tevatron $p\bar{p}$ collider at Fermilab (which comes online in fall 1986), SLC at SLAC, and if they exist (and if it exists) at the SSC for certain. Discovering the LSP and determining its properties (mass, interaction cross section, etc.) would allow one to reliably calculate its relic abundance and settle the issue of whether or not it could be the dark matter. Needless to say, knowing the dark matter constituent's properties would make direct searches much more straightforward.

Experiments to directly measure the mass of the electron neutrino continue. A confirmation of the result of the ITEP group (Lubimov etal. 1981) would be strong evidence that the Universe is neutrino-dominated (and cosmologists and structure simulators would have to adjust accordingly!). The continuing neutrino oscillation experiments also bear on this issue.

5. A HOST OF DARK MATTER PROBLEMS

As a number of authors have emphasized there are several dark matter problems (see, e.g., Freese and Schramm 1984, Schramm 1986, Carr 1986, and Bahcall 1984). Bahcall (1984) has made a convincing case that there is an unaccounted for, dark disk component in our galaxy, with mass density comparable to the seen component (stars, gas, dust, etc.). If typical of spiral galaxies in general, this dark disk component corresponds to $\Omega \simeq 0.005$. Since the formation of the disk involved dissipation, it is unlikely that this component is comprised of WIMPs. In all likelihood it is baryonic (which does not conflict with the nucleosynthesis bounds and in fact receives weak confirmation as primordial nucleosynthesis suggests that $\Omega_{baryon} \gtrsim 0.014$, which is about twice that seen in luminous matter).

As we have heard at this symposium there is very good evidence for the existence of a dark halo component in spiral galaxies. Since there is no convincing evidence as of yet for a rotation curve which 'turns over', at present we only have a lower bound to the amount of dark matter in the halos of spiral galaxies, something like $\Omega \gtrsim 0.05 - 0.10$.

There is also good evidence for dark matter in clusters of galaxies and (somewhat weaker evidence) for dark matter in small groups of galaxies. In the case of clusters, some of this matter is only dark as far as the optical astronomer is concerned, since it is X-ray bright. The uncertainties here are much greater, but the amount of dark matter in clusters probably corresponds to $\Omega \simeq 0.1 - 0.3$.

Finally, there is the ultimate dark matter problem. The 'light' of theory casts a strong beam on $\Omega = 1.0$, the flat, Einstein-deSitter model. While the 'shadow' of observation is cast on the value $\Omega_{obs} \simeq 0.2 \pm 0.1$ (where $\pm$ 0.1 is not meant to be a formal error bar, but rather a theorist's estimate of the spread of current determinations). To be sure, the observational determinations only apply to the matter which clusters with the visible matter on scales less than 10–30 Mpc. A component which is smoothly distributed on these scales would thus far have gone undetected. In order to reconcile theory with observation, this smooth, dark component would need to contribute $\Omega_{SM} = 1 - \Omega_{obs} \simeq 0.8 \pm 0.1$.

5.1 The Ω Problem

This discrepancy between theory and observation has come to be known as the Ω problem. A variety of ideas have been put forth to save the flat, $\Omega = 1$ (more precisely $k=0$) Einstein-deSitter model. They are all based upon the same principle, a smooth component contributing about

$$\Omega_{SM} \simeq 1 - \Omega_{obs} \simeq 0.8 \pm 0.1$$

Suggestions for the smooth component include: failed galaxies (Kaiser 1984); a relic cosmological term (Peebles 1984, Turner, Steigman, and Krauss 1984); fast-moving, light strings or a network of light strings (Vilenkin 1985; 'light' here means a symmetry breaking scale << 10^{16} GeV, the canonical scale for cosmic strings which would lead to interesting isothermal perturbations); and relativistic particles produced by decaying WIMPs (Turner, Steigman, and Krauss 1984, Dicus, Kolb, and Teplitz 1978, Gelmini, Schramm, and Valle 1985, Olive, Seckel, and Vishniac 1985), I will briefly discuss the exotic (even by present standards) scenario of relic WIMPs decaying into WIRPs (Weakly-Interacting Relativistic Particles).

[A brief comment with regard to a relic cosmological term. A cosmological term corresponds to a uniform energy density and has exactly the same form as the vacuum energy density associated with a quantum field theory (Zel'dovich 1968). For this reason one might look to particle physics for a prediction for any relic cosmological term. The quantum contribution to the vacuum energy (or zero point energy) for a renormalizable theory is formally infinite, one of the infinities which is swept under the rug by renormalization. Forgetting about the infinity for a moment, there is no symmetry in the theory which excludes a vacuum energy as large as m_{pl}^4, and each stage of SSB should change the vacuum energy by order M^4; recall the present expansion rate of the Universe sets an upper bound to the vacuum energy density of about 10^{-46} GeV^4. The present theoretical situation then is somewhat discouraging; first one has to throw away an infinite contribution, then one has to fine-tune away terms in the theory which are permitted by all the symmetries of the theory (and if not put in ab initio would arise due to quantum corrections anyway) and which are 122 orders-of-magnitude larger than the present upper limit to Λ -- not much theoretical guidance here! There is one tiny ray of hope though. In supersymmetric theories, the fermionic and bosonic contributions to the vacuum energy cancel and the cosmological constant is zero. However, once SUSY is broken this cancellation no longer occurs and the vacuum energy becomes of order $\langle\phi\rangle^4$ or about 10^{10} GeV^4. Unless the Universe is really supersymmetric and we don't realize it, which doesn't seem likely, the apparent smallness of the cosmological constant, relative to what it has every right to be, is a very fundamental problem. That doesn't, however, preclude a solution (e.g., an axion-like mechanism) which leaves a tiny relic cosmological constant, say 0.8 of critical density or so.]

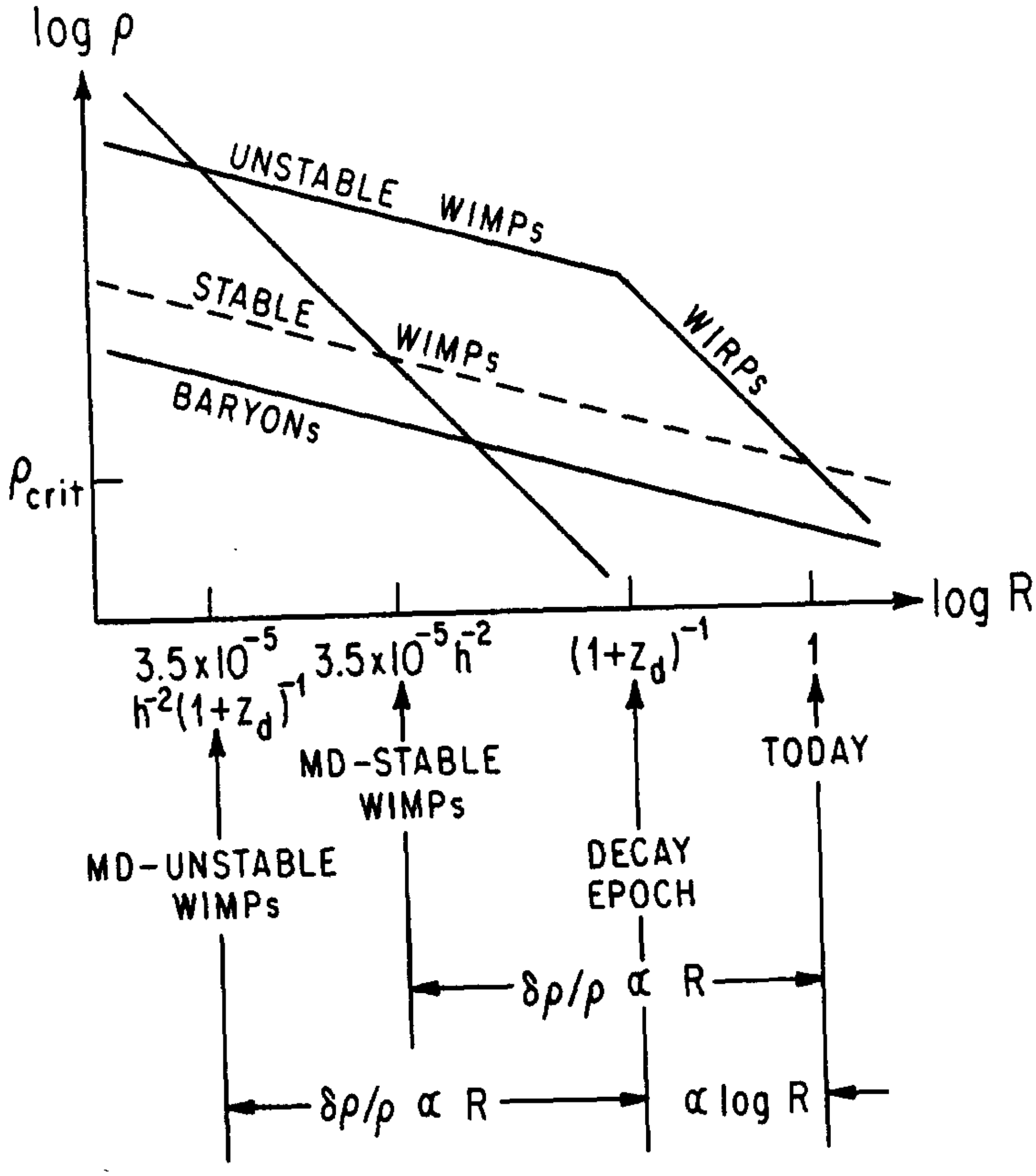

Figure 8 - Schematic summary of structure formation with 'rotting particles' (and the stable WIMP scenario for comparison).

5.2 Structure Formation with 'Rotting Particles'

The basic idea of this scenario is that today the Universe consists of two components: NR particles which account for the mass which clusters, i.e., $\Omega \approx 0.2 \pm 0.1$; and R particles, which by the virtue of their high speed cannot cluster and account for the remaining $\Omega \approx 0.8 \pm 0.1$. (For simplicity's sake, it would be preferrable for the NR component to be baryons only.)

It has been long realized that density perturbations cannot grow in a Universe which is radiation-dominated, and so it is necessary that the R particles have a recent origin. In the rotting scenario, they are born from the non-radiative decays of unstable WIMPs. In order to account for the observed structure in the Universe the decays occur rather recently, redshift of order 3-10 (corresponding to a WIMP lifetime of around 10^8 - 10^9 yrs).

[In some particle physics models which address the so-called family problem, why are there 3 families, etc., there are new interactions which would allow a heavy neutrino to decay into a light neutrino and a massless, very weakly-interacting (essentially invisible) Nambu-Goldstone boson, with a lifetime which is about right for this scenario.]

For definiteness, let's suppose that the unstable WIMP is a neutrino and that $h = 0.5$. If the neutrino were stable then its mass would have to be about 24 eV to achieve $\Omega = 1$. Because the mass density in WIRPs scales like R^{-4} since the decay epoch (say redshift z_d), the neutrino mass required in the decaying scenario is about $24z_d$ eV. This in turn means that in the decaying scenario the Universe becomes matter-dominated earlier than in the non-decaying case, by a factor of z_d. Hence, density perturbations start to grow earlier; of course once the Universe becomes radiation-dominated they cease growing. They start growing earlier but stop growing before the present epoch -- the net effect is that they undergo the same amount of growth (actually, slightly more growth; after the decays, perturbations continue to grow logarithmically). In the case of a decaying neutrino the damping scale is smaller because the mass of the neutrino is larger. As White has discussed (1986a,b), this helps the viability of the neutrino scenario. The so-called 'rotting' particle scenario is summarized in Fig. 8.

What can one say about z_d? Since perturbations undergo about the same amount of growth, independent of z_d, perturbations at the epoch of decoupling are larger for larger z_d. This in turn implies larger anisotropies in the microwave background. Present observations probably constrain z_d to be less than about 5-10 (Vittorio and Silk 1985, Turner 1985).

Before I forget, the rotting particle scenario does have one drawback. It predicts a very youthful Universe, typically $H_o t_o \approx 0.53$ - 0.58. Unless the Hubble constant is in the range 40-55 km $\sec^{-1}$ Mpc^{-1}, rotting particles are in deep trouble.

5.3 Testing Oddball Cosmological Models

Is it possible to use observational data to discriminte between the

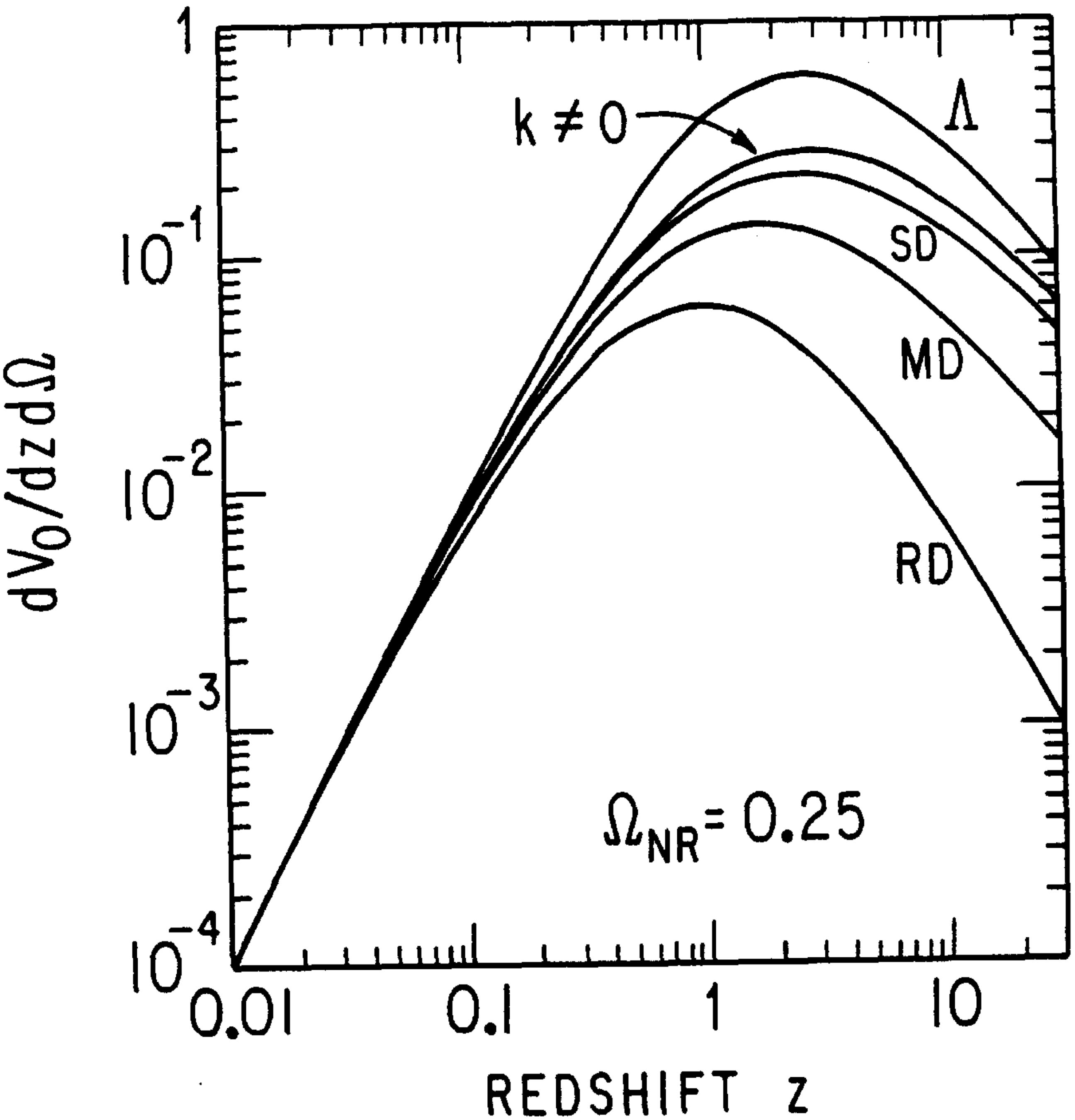

Figure 9 - The differential comoving volume, $dV_o/dZd\Omega$, vs. redshift z, for model universes with $\Omega_{NR} = 0.25$ and k = 0 ($\Lambda \neq 0$, smooth component of matter, fast strings, and relativistic particles); also shown for comparison is the $k \neq 0$ model (from Charlton and Turner 1986).

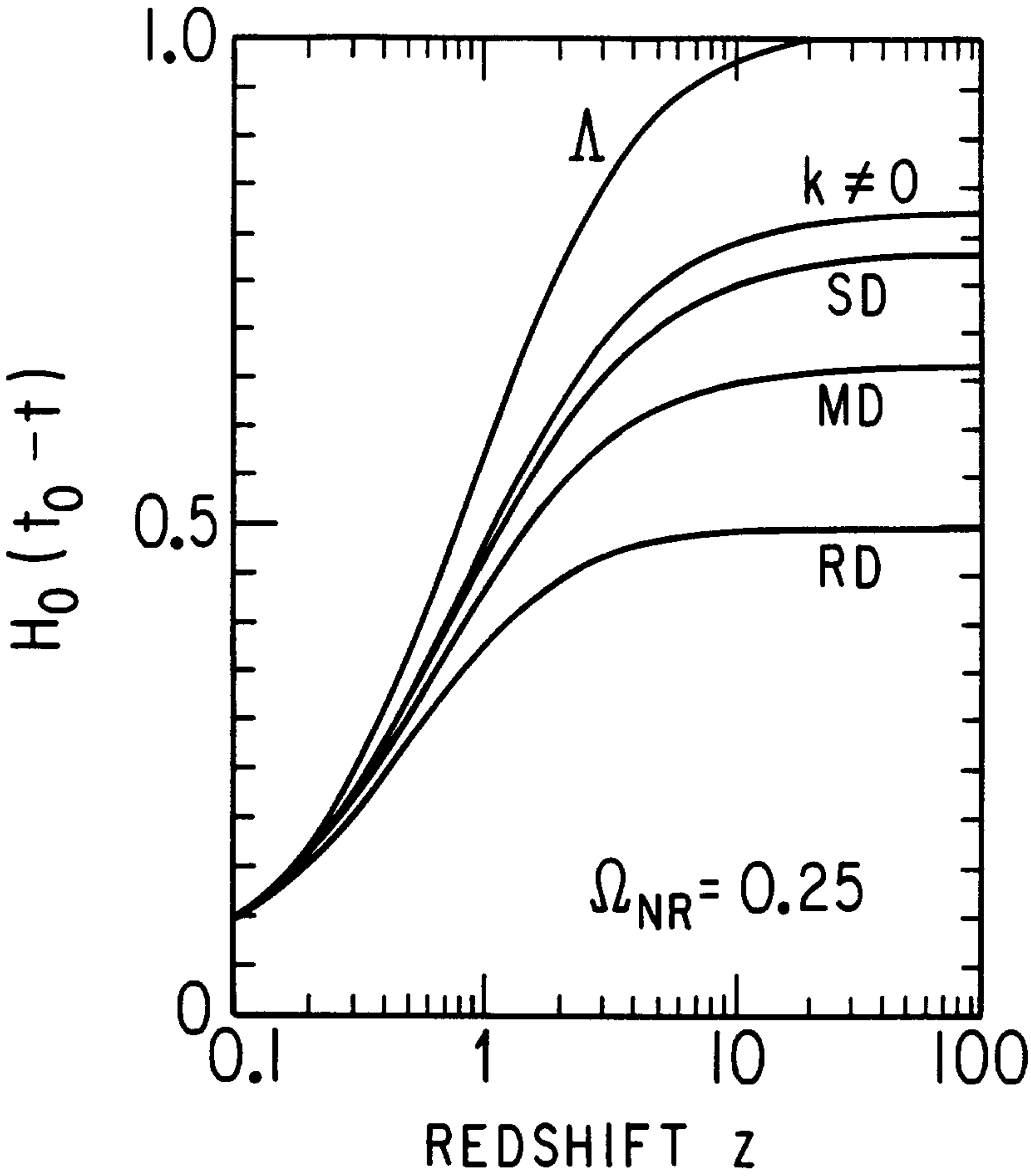

Figure 10 - Lookback time, $H(t_o - t)$, vs. redshift z, for the same models as in Figure 9 (from Charlton and Turner 1986).

theoretical ideas which have been put forth to save the flat Universe? [I have nightmares of a modern day Christopher Columbus proving all of us theorists wrong.] A graduate student working with me thinks the answer might be yes. Since the evolution of the cosmic scale factor in these models (rotting particles, relic cosmological term, fast moving strings) is very different from the usual $R(t) \propto t^{2/3}$, in a flat, matter-dominated Universe, one might expect that some of the usual cosmological tests might be good discriminators. She has recently calculated the magnitude vs. redshift, angular size vs. redshift, lookback time vs. redshift, and differential comoving volume element vs. redshift diagrams for these models. The two diagrams which look to be particularly useful are shown as Figs. 9,10 (from Charlton and Turner 1986).

6. PROGNOSTICATIONS AND CONCLUDING REMARKS

6.1 Great Dark Hopes

What are the most likely candidates from the new particle zoo for the dark matter? Unfair question -- but I'll answer it anyway. I would say the axion, the light neutrino, and the photino (or another LSP candidate).

<u>Axion</u> -- The Peccei-Quinn mechanism continues to be the most attractive solution to the only woe of QCD, the strong CP problem. Many SUSY models automatically have a PQ symmetry and indications are that the field theory limit of the superstring also has a PQ symmetry. The PQ symmetry breaking scale required for axions to dominate the Universe, an energy greater than about 10^{12} GeV, is an interesting scale. Finally, it seems possible that halo axions could be detected (especially if theorists could predict their mass more precisely).

<u>Light Neutrino</u> -- The neutrino is actually known to exist! Almost all theories beyond the standard model predict that neutrinos should have masses (albeit very small). With the neutrino one gets at least 3 (and possibly 4) shots at being right (I'll bet on the τ-neutrino). What about the experimental prospects? A recent paper by Bergkvist (1985) raises some serious questions about the validity of the ITEP experiment. [Bergkvist has shown that the line used to calibrate the ITEP detector has a non-Lorentzian tail, which he claims would give rise to the non-zero result they obtain for the neutrino mass.] In any case enough different types of experiments to determine the electron neutrino mass are now in progress that we should have a definitive answer soon. With regard to neutrino oscillation experiments, Boehm and Vogel (1984) have recently reviewed the experimental situation and find no conclusive evidence for the existence of neutrino oscillations. The experimental effort in this direction, however, continues.

John Simpson (1985) has recently caused some excitement with the results of his tritium endpoint experiment (which employs a Si(Li) detector). His data indicate a kink in the Kurie plot, which could be explained by the existence of a 17.1 keV neutrino mass eigenstate with about 3% mixing to the electron neutrino weak eigenstate.

The theoretical implications are very exciting. In order for his result to be consistent with other experimental data, there must be two 17.1 keV mass eigenstates (Dugan etal. 1985). Cosmology tells us that such a neutrino(s) cannot be stable and have the canonical abundance. Either it must have a smaller relic abundance or have a lifetime of less than about a year in order to avoid interfering with structure formation in the Universe (Steigman and Turner 1985). Either alternative implies that neutrinos must be endowed with interactions other than the usual electroweak interactions (e.g., as in the majoron model of Gelmini and Roncadelli 1981). If this is the case, neutrino annihilations will be more effective, keeping them in equilibrium until much lower temperatures, which results in their having a much smaller relic abundance (cf, Eqn. (3) or Kolb and Turner 1985). In fact, if they have these additional 'stronger than weak' interactions and are stable, their relic abundance could be such that they are the dark matter. It is interesting to note that in this case they would behave like cold dark matter.

Hold everything! Two other groups have now looked for the same effect in the decays of ^{35}S (Q value of 166.8 keV) and at the 90% confidence level set a limit on the mixing of a mass eigenstate greater than about a few keV of less than 1% (Altzitzoglou etal. 1985, Markey and Boehm 1986).

Simpson has worried that the kink might be due to a solid state effect (or Coulomb effects) since the kink occurs so near threshold and he plans to look at the tritium β-decay spectrum with a Ge(Li) in the near future.

Photino (or another LSP candidate) -- SUSY is a very attractive theoretical idea and just as importantly it makes predictions which can be tested in the forseeable future. Thus far, none of the experimental data provide any unambiguous evidence for SUSY. However, all of the SUSY candidates suggested for the dark matter should be able to be produced at CERN, Fermilab or the SSC. We will have an answer, maybe not tomorrow, but before the turn of the century. In addition, there is the very real possibility that if relic LSPs are the halo dark matter, they or their effects can be detected. Of all the spartners, a 1-10 GeV photino seems to be the most likely LSP candidate.

My Favorite Dark Horse Candidates -- A planck mass monopole which does not catalyze nucleon decay could provide the halo mass density, close the Universe and safely elude all the astrophysical bounds (see Fig.6). Not only that, but its flux ($\approx 10^{-13}$ cm^{-2} sr^{-1} sec^{-1}) is such that detection is just around the corner! For personal reasons as well as for the novelty of it I also include shadow matter in my dark horse list. Quark nuggets are so attractive that they too have to be included as a dark horse possibility.

6.2 Concluding Remarks

So much for prognostications (the majority of which must necessarily be wrong!). The organizers of this symposium have flattered me by asking that I review all the exciting dark matter candidates from the new particle zoo. Now for the harsh realities. God forbid, but it is very possible that we live in a low Ω, baryon-dominated Universe. After all, we are only compelled to appeal to non-baryonic dark matter if Ω is greater than about 0.15 (higher if we are foolish enough to ignore the primordial nucleosynthesis constraint of $\Omega_{baryon} \lesssim 0.035h^{-2}$). Theoretical prejudice aside, there is no convincing evidence (or even unconvincing evidence for that matter) that Ω is any larger than about 0.2±0.1. History repeats itself; once again we have convinced each other that there are only two possible stories of structure formation -- cold and hot dark matter with $\Omega = 1$. We may be in for some real surprises. Fortunately, it's not surprises that puts theorists out of work, rather more often it's the lack of surprises. [There is an old saying which dates back to the early days of experimental physics; theorists untethered by experimental data are doomed to rise in their own hot air never to be seen again.] Perhaps it will be a scenario based upon cosmic strings or the role of astrophysical fireworks (see Ostriker's contribution to these proceedings) that will eventually prevail; then again, it could be an $\Omega = 1$ WIMP-dominated Universe. Now I'm covered either way!

Acknowledgements. I am grateful to a multitude of colleagues for enlightening discussions. This work was supported in part by the Department of Energy (at Chicago and at Fermilab), by the National Aeronautics and Space Administration (at Fermilab), and by an Alfred P. Sloan Fellowship.

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